Scattering of Dust Particles With Nonzero Dipole Moments

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***Abstract*— The process of scattering of one dust particle on another dust particle in complex plasmas is considered. The dipole moments of dust particles are taken into account. The results on the scattering angle and scattering cross section are presented, and the interesting effect of zero-angle dust particle–dust particle scattering is predicted.**

***Index Terms*— Dusty plasma, scattering cross section.**

I. Introduction

THE INFLUENCE of dust particle polarization is the subject of intensive investigations, as it plays an important role in the physics of interstellar dust and the physics of the ionosphere [1], [2]. The mechanism of dust particle polarization depends on the plasma surrounding the dust particle. The dipole moment of a dust particle can appear due to the flow of ions or electrons, the action of an external electrical field, or the field of another dust grain [3], [4]. Experimental measurements of the dipole moment of a dust particle in a gas discharge plasma have been made recently in [5].

It is well known that in order to correctly describe the scattering process in plasmas, it is necessary to take into account the effect of charge screening. The effective screened interaction potential (taking into account the charge–dipole interaction) was obtained in [6], where the scattering process in complex plasmas was studied with the assumption that the dipole moment of a dust particle did not change during scattering. This approximation is correct when the dipole moment is induced by an external electric field or the flow of ions, and such a situation can occur in experimental complex plasmas. However, in the case of interstellar dusty plasma or dusty plasma in the ionosphere, the dipole moment of the dust particle can be induced by the electric field of another dust particle. In this case, the dipole moment of a dust particle is not constant during the collision between two dust particles. In this paper, we consider this particular case.

In Section II, we introduce the effective screened interaction potential used in this paper and the scheme used to calculate the scattering angle and the scattering cross section. In Section III, the results are presented and discussed.

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II. Dust Particle–Dust Particle Interaction Potential

For the interaction potential between dust particles, we took the effective screened potential proposed in [6]

$$\Phi_{dd}(r) = \frac{e^2 Z^2}{r}\exp(-rk_D) + \frac{eZ\Delta d(r)}{r}\left[\frac{1}{r} - \frac{k_D}{2} f(r)\right] \quad (1)$$

where $-eZ$ is the charge of the dust particle, k_D is the screening length (the inverse value of the Debye length λ), $\Delta d = (\vec{d}_1 - \vec{d}_2)\vec{n}$, $\vec{d} = \vec{d}(r)$ is the dipole moment of the dust particle depending on the distance between dust particles, $\vec{n}$ is a unit vector connecting the centers of dipoles $\vec{d}_1$ and $\vec{d}_2$, and

$$f(x) = \exp(-xk_D)Ei(xk_D) - \exp(xk_D)Ei(-xk_D)$$

$$Ei(-ax) = -\int_x^{\infty} dx\ \exp(-ax)/x$$

$$Ei(ax) = \int_{-\infty}^{x} dx\ \exp(ax)/x.$$

The first term in (1), which coincides with the well-known Yukawa potential, describes screened charge–charge interaction. The second term in (2) is responsible for the screened charge–dipole interaction. The interaction potential (1) neglects a pure dipole–dipole interaction. Therefore, we are limited by the values of dusty plasma parameters, under which the charge–charge interaction and charge–dipole interaction are stronger than the dipole–dipole interaction.

To describe the coupling strength between dust particles, we introduce the following dimensionless parameters.

1) $\beta = e^2Z^2/mv^2\lambda$, where m is the dust particle mass and v is the initial velocity of the dust particle before collision.
2) $\alpha = |\Delta d(\lambda)|/(eZ\lambda)$. Here, we take $\alpha < 1$, as we neglect the term responsible for the dipole–dipole interaction in (1).

The parameter α describes the value of the dipole moment when the distance between two considered particles is equal to the screening length λ. Further, as the dipole moment of the first dust particle is induced by the field of the second dust particle with which it collides (and vise versa), we will consider the case $\Delta d < 0$. In this case, the particles would have the same–opposite directional dipole moments. The problem becomes central (the interaction axis passes through

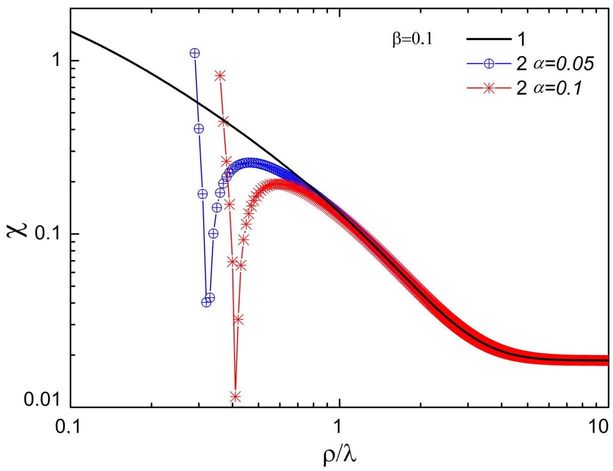

Fig. 1. Dust particle–dust particle scattering angles obtained using the Yukawa potential (line 1) and the potential (1) (line 2) for different values of α at $\beta = 0.1$.

the centers of point-like dust particles), but the magnitude of dipole moments becomes dependent on the distance between the particles. We take the linear dependence of a dust particle's induced dipole moment on affecting electric field $\boldsymbol{E}$ of another dust particle. As we consider the case where the Yukawa term is dominant in interparticle interaction, the following relation for the induced dipole moment was used:

$$|\delta d(r)| = |\delta d(\lambda)| \frac{\lambda^2}{2\lambda^2}\left(1 + \frac{r}{\lambda}\right) \exp\left(1 - \frac{r}{\lambda}\right). \tag{2}$$

The classical scattering angle for two particles with the interaction potential (1) for a given impact parameter ρ is equal to

$$\chi(\rho) = |\pi - 2\varphi(\rho)| \tag{3}$$

where

$$\varphi(\rho) = \rho \int_{r_{\min}}^{\infty} \frac{dr}{r^2\sqrt{1 - U_{\text{eff}}(r,\rho)}} \tag{4}$$

and U_{eff}, an effective interaction energy in units of kinetic energy of the projectile, has the following form:

$$U_{\text{eff}}(r,\rho) = \frac{\rho^2}{r^2} + \frac{2\Phi_{dd}(r)}{mv^2}. \tag{5}$$

In (5), the centrifugal force is taken into account. The distance of the minimal approach $r_{\min}$ at a given ρ is obtained from the equation $U_{\text{eff}}(r_{\min}, \rho) = 1$. The scattering cross section can be obtained using (3) from the following formula:

$$\sigma = 2\pi \int_0^{\infty} (1 - \cos\chi(\rho))\rho d\rho. \tag{6}$$

III. Results and Discussion

In Figs. 1–3, the scattering angles calculated using the interaction potential (1) are presented. It is seen that for small values of the parameter β, the charge–dipole interaction gives a strong deviation from the result obtained using the Yukawa potential. At some values of the impact parameter, the scattering angle has extremely small values (line 2 in Figs. 1 and 2) in comparison with the case in which the charge–dipole interaction is neglected (line 1 in Figs. 1 and 2). This effect is caused by the charge–dipole attraction,

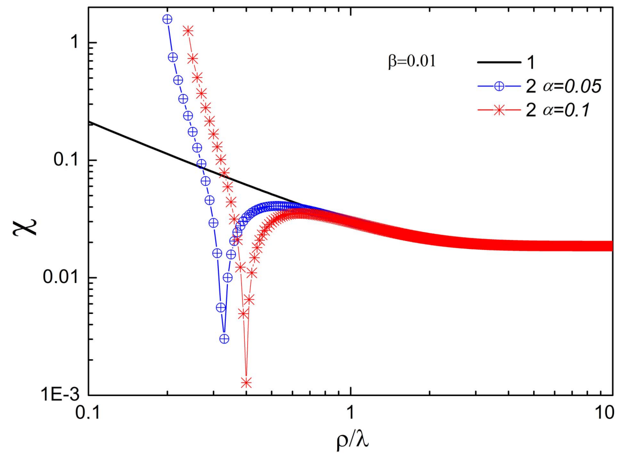

Fig. 2. Dust particle–dust particle scattering angles obtained using the Yukawa potential (line 1) and the potential (1) (line 2) for different values of α at $\beta = 0.01$.

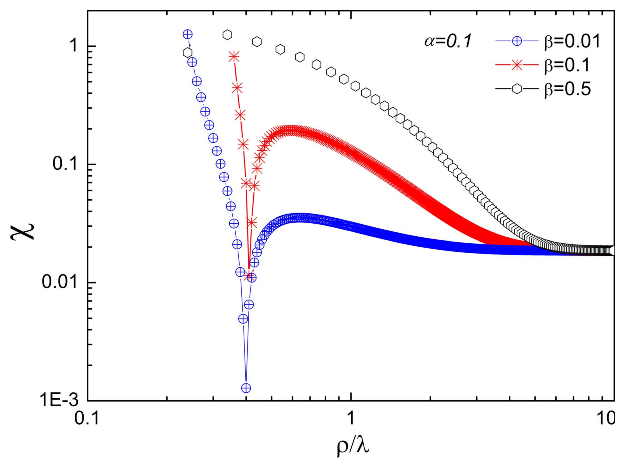

Fig. 3. Dust particle–dust particle scattering angles obtained using the potential (1) for different β values at $\alpha = 0.1$.

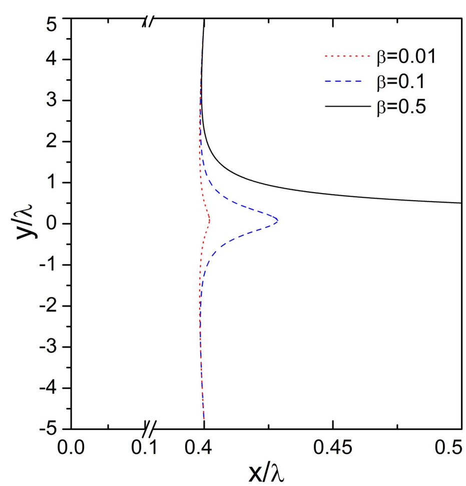

Fig. 4. Dust particle trajectories during collisions for different values of β at $\alpha = 0.1$. The scattering center is located at ($x = 0$, $y = 0$).

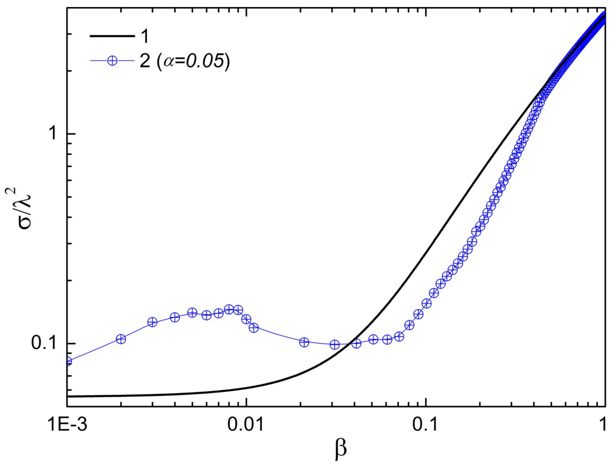

Fig. 5. Dust particle–dust particle scattering cross section obtained using the Yukawa potential (line 1) and the potential (1) (line 2) at $\alpha = 0.05$.

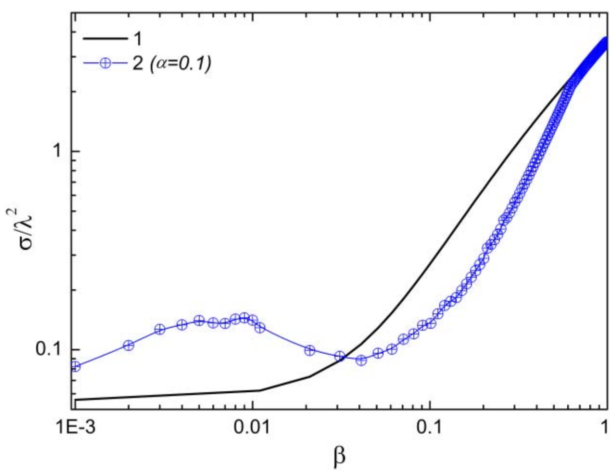

Fig. 6. Dust particle–dust particle scattering cross section obtained using the Yukawa potential (line 1) and the potential (1) (line 2) at $\alpha = 0.1$.

which becomes stronger than the charge–charge repulsion term in (1) at small interparticle distances. When the parameter β increases, *this zero-angle scattering* effect disappears, as observed in Fig. 3. At large values of β (low kinetic energies), the scattering is governed by long-range repulsion, the first term in (1), whereas at small β values (high kinetic energies), particles are able to come within very small distances to each other, where the attraction due to charge–dipole interaction becomes dominant. The trajectories of the scattering dust particle, shown in Fig. 4 for three values of parameter β, lend support to this assertion.

The impact of the charge–dipole interaction on the scattering cross section can be observed from Figs. 5 and 6, where the scattering cross sections for different values of parameter α are shown. The appearance of the dipole moment of the dust particles can increase the scattering cross section at relatively large β values, while also decreasing the scattering cross section at small β values.

IV. Conclusion

The investigation of dust particle–dust particle scattering cross sections shows that dipole–charge interaction may have a strong impact on elementary processes in a complex plasma. It can be concluded that the dust particle polarization effect, which can be neglected in cases of strong coupling ($\beta \gg 1$), must be taken into account in cases of weak coupling ($\beta < 1$, this condition corresponds to what is usually referred to as a gaseous state in a system of charged dust particles).

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